Selective Reaching: Evidence for Action-Centered Attention

Steven P. Tipper and Cathy Lortie
McMaster University, Hamilton, Ontario, Canada

Gordon C. Baylis
University of California, San Diego

Most studies of selective attention briefly present static 2-dimensional stimuli and require arbitrary responses such as verbal naming or a keypress. Many of our perceptual–motor interactions with the environment, however, require reaching directly toward an object while ignoring other objects in the scene. A series of experiments examines selective attention in the latter reaching situation. Effects previously observed in the traditional experimental procedures were obtained, suggesting that the models developed (which propose inhibitory mechanisms, e.g.) apply to ecologically valid situations. Attention accesses action-centered internal representations during such tasks.

Most biological organisms inhabit complex environments. The objects that comprise such an environment afford a variety of actions. Therefore, if an organism is to achieve a specific goal, its behavior must be highly selective. The study of selective attention examines the mechanisms that enable complex perceptual information to be constrained to control specific actions.

The problem of selecting from complex perceptual inputs is ubiquitous. A person reaching for a particular glass of beer from a table containing many glasses, or the pike attempting to attack one of a number of stickleback prey, face similar problems of selection. That such selection abilities are crucial for coherent behavior is clearly evidenced from individuals suffering from head injury (Geschwind, 1982) or clinical syndromes such as schizophrenia (Frith, 1979). In these cases, both thought and action may be disrupted by stimuli irrelevant to the task at hand.

The study of attention has a long history, from James's (1890) insights to the beginnings of experimental study (Broadbent, 1958; Cherry, 1953) to the current theories of Posner (Posner & Petersen, 1990) and Treisman (1988), which attempt to link cognitive and neurophysiological explanations. Hence, a much better understanding of the role of attention in perception and the mechanisms of attentional selectivity has been achieved. In understanding processes such as attention, however, it is essential that the environment in which the organism evolved and the behavioral requirements for survival in that environment be considered (Gibson, 1979; Marr, 1982). Perceptual action systems have evolved in terms

of the fundamental behavioral situation in which actions are aimed directly at objects within a three-dimensional (3D) environment.

Such considerations of behavior have tended to be neglected in studies of selective attention. Rather, a wide variety of paradigms have been used that typically present brief, two-dimensional (2D) stimuli and require arbitrary responses. For example, Tipper (1985; Tipper & Driver, 1988) presented red to-be-attended drawings superimposed on green to-be-ignored drawings. These displays were presented for approximately 100 ms and followed by a pattern mask. Subjects were required to name or provide the superordinate category of the red drawing.

An obvious limitation of the models developed from such experiments is that the task situations are rarely encountered in "normal" interactions with our environments. For example, we rarely select red transparent objects superimposed over green objects; visual information is typically available continuously rather than in masked 100-ms flashes (see Haber, 1983), and most adults do not overtly name or categorize objects they encounter in the world. This latter arbitrary experimental stimulus–action coupling does not consider an organism's typical behavioral requirements.

As von Hofsten (1987) pointed out, perception and action evolved together to provide the temporal and spatial constraints that enable successful interactions with the environment. Although arbitrary responses to a perceptual input can be produced, perception comes easier to some tasks than others. For example, Stravenski and Hansen (1978) found that even though subjects could not identify the location of a target when responding verbally, they were extremely accurate when directly striking the location. Similarly, studies of blindsight show that even when there is no access to verbal-conscious processes, location is analyzed and can be accessed by pointing (Weiskrantz, 1986; for similar observations, see Bridgeman, Lewis, Heit, & Nagle, 1979; Wong & Mack, 1981). Thus in some situations, perceptual information not available for verbal report is nevertheless accessible by the motor system.

We therefore intend to examine selective attention in tasks that require direct manual contact by using a stimulus set in a 3D experimental situation. There are three motives for this approach. The first and most obvious is that it is necessary to

examine whether the effects observed in traditional experimental tasks, such as interference and negative priming (to be described later), are also observed in the new situation. This is a fundamental issue because models of attention are determined by empirical observations. If those observations cannot be made in a variety of situations, then the models of attention may have limited scope.

Second, because many of the studies of selective attention require arbitrary symbolic responses, such as naming stimuli, it is not possible to undertake the same experiments with other species. Thus animal models cannot be developed, and investigation of the underlying neurophysiology of selective attention is limited. The simple perceptual–action tasks to be used here can be easily undertaken by infrahuman primates and therefore may open up this area for different levels of inquiry.

Finally, the approach adopted here enables examination of the forms of internal representation accessed when subjects are required to direct action toward an object while ignoring a distractor object presented simultaneously. We first discuss three forms of internal representation that have been proposed by researchers in computational vision as necessary frames of reference for the range of visual–spatial tasks of which humans are capable. We then propose a fourth frame of reference that we believe is necessary for motor responses directed to stimuli in 3D space.

2D Retina-Centered Framework

Distractor interference is manifested by reduced speed and/ or accuracy of responding to a target object when a distractor is present. For example, a subject's response time to identify a target letter is longer when an irrelevant to-be-ignored letter is in the scene than when the target is presented alone. Such a result suggests that the distractor is analyzed and competes with the target for the control of action. Interference effects have been observed in a variety of species, including humans (Stroop, 1935), fish (Neill & Cullen, 1974), and frogs and toads (Ingle, 1973). Therefore, any general model of attention must be able to account for distractor interference. Some models have attempted to describe interference effects in terms of a 2D retina-centered framework. For example, B. A. Eriksen and C. W. Eriksen (1974) reported that distractors produce significant interference only when they are within 1° of visual angle of the target (see also Hoffman & Nelson, 1981; Posner, Nissen, & Ogden, 1978). Such a view argues that selective attention is analogous to a spotlight (Broadbent, 1982; LaBerge, 1983) or zoom lens (C. W. Eriksen & Rohrbaugh, 1970; C. W. Eriksen & St. James, 1986) that accesses a retina-centered representation. The resolution of this spotlight is limited to about 1° of visual angle, and distractors that are within the beam are analyzed by the attentional system and thus interfere with the target.

This retina-centered representation may be similar to the primal sketch proposed by Marr (1982), as attention is assumed to select low-level physical features for subsequent identification processes (i.e., early selection models; see Broadbent, 1958). The important property of this model, for our current purposes, is that attentional processes will be determined by the retinal projection of stimuli and not by the 3D structure of the experimental environment.

3D Viewer-Centered Framework

Downing and Pinker (1985) and Gawryszewski, Riggio, Rizzolatti, and Umilta (1987) examined the spatial properties of attention in 3D space. Subjects were required to fixate visually a central point while orienting attention to cued positions in front of or beyond fixation. The important observation was that response time costs for invalidly cued trials were greater when attention was focused to the near location than when it was directed to the far location. One account of this "near" effect postulated that an attentional space is created from the viewer to the attended location. Thus, when attention is oriented to the far position, near stimuli in the uncued location fall within the attentional space and can therefore be analyzed more rapidly. When attention is focused on the near location, however, uncued objects in the far position fall outside the attentional space.

Downing and Pinker (1985) proposed that visual attention selects information from a representation that contains 3D information. This representation may be similar to the viewer-centered 2½D sketch proposed by Marr (1982). This "depth map" was assumed to be the first representation of the visual world from which cognitive processes such as selective attention could read information. The important point about the 2½D sketch is its viewer-centered nature. The attentional space is determined by the subject's viewpoint. Thus a change in view due to eye, head, or body movement would change this representation.

Environment-Centered Framework

Hinton and Parsons (1988) also examined visual processing in 3D environments. They asked whether environment- or viewer-centered representations are used when subjects compare the shapes of objects at different orientations. Two objects were placed in front of the subject so that they were separated by either 90° or 150° of visual angle. The subject then (physically) rotated one of the objects until he or she was able to decide if they were identical or mirror images. The major finding was that subjects rotated the objects so that they had the same relationship to the table top and room, even though this orientation produced quite different retinal images of the two objects being compared. The results suggested, therefore, that people tend to rely on environment-centered representations more than viewer-centered representations. Studies of inhibition of return have come to similar conclusions when demonstrating that attentional cuing effects are determined by environmental loci independent of eye movements (Maylor, 1985; Posner & Cohen, 1984).

The most striking feature of environment-centered representations, which have been described in a computational model as the "scene buffer" (Hinton, 1981), is that they remain stable independently of eye or body movements. A further point concerning environment-centered representations is that they have properties similar to object-centered

representations. That is, object-centered representations are described in terms of how the parts of an object relate to one another. Similarly, environment-centered representations can be considered as a more global form of representation in which the relationship between objects is described.

It is clear that there are many frames of reference in which information can be represented. The frame of reference is generally determined by task demands. Target detection can be undertaken within a viewer-centered depth map, whereas shape matching is best achieved in environmental coordinates. We are currently concerned, however, with tasks that require selective action to be directed to a target while a distractor object is ignored. An important contrast with the studies discussed so far is that the task requires a direct reaching action toward a stimulus. In this situation, it is possible that neither 2D retina-, 3D viewer-, nor environment-centered visual representations would be adequate. Rather, we propose that action-centered representations are necessary.

Action-Centered Representations

Perception and action are typically studied as two distinct fields. As discussed, however, perception and action have evolved together. Perception provides the visual information on which we act. The idea that perception is independent of action has been questioned by Gibson (1979) and Turvey and Carello (1986); rather, what is perceived depends on the action to be performed (Bootsma, 1989).

The effect of action on perceptual tasks has previously been well established. Both adaptation to distorting lenses (Held & Mikaelian, 1964) and recovery of visual capacity after lesion to the striate cortex (N. K. Humphrey, 1974) can be achieved best when observers act on 3D environments. Similarly, other experimental manipulations show the influence of action on perception. Michaels (1989) demonstrated that the pattern of results produced when subjects were required to move a toggle switch to the right or left of stimuli presented above or below fixation was determined by where the hand was placed, that is, whether it was at the body midline or 30° to the right or left of midline. Similarly, preknowledge of the hand used to make a response can influence the effects of attention in determining whether a stimulus–response compatibility effect is obtained (Verfaellie, Bowers, & Heilman, 1988).

Clearly, therefore, the effects observed in such attention tasks are not determined purely by perception; the interplay between perception and action is crucial. These speculations concerning the link between perception and action have interesting implications for the role of the active observer in selective attention tasks. Consider the situation in which a subject rapidly reaches for a target stimulus while avoiding action toward irrelevant distractors. Although visual information is obviously necessary in guiding the hand to the stimulus, the principal attentional task is to respond to the target with the hand. The relationship between the target and distracting stimuli with the hand may, therefore, be more important for selective action than either 2D retina-, 3D viewer-, or environment-centered visual information. Thus it might be reasonable to assume that in such a situation

selective attention is determined by action-centered representations.

The experiments to be described attempt to investigate the following issues: (a) whether effects similar to those observed in traditional attentional paradigms can be observed and (b) what form of internal representation is accessed by the selective attention system when direct spatial response to a stimulus is required. To preview our findings, Experiment 1 discounts both 2D retina- and environment-centered representations, and it provides suggestive evidence against a 3D viewer-centered frame. Experiment 2 manipulates hand location to unconfound 3D viewer- and action-centered representations and finds support for the latter. Experiment 3 manipulates hand of response and provides further evidence against viewer-centered representations. Experiment 4 tests an alternative retina-centered explanation for the results and finds further support for action-centered representations. Finally, Experiment 5 provides converging evidence for the action-centered representation hypothesis when examining inhibitory mechanisms of selection.

Experiment 1

Figure 1 represents the layout of the stimulus display. A board containing a set of buttons is placed on a table in front of the subject. The subject's task is to depress the button with the red light adjacent to it and to ignore the yellow light. The experiment examines the interference effects produced by the irrelevant yellow light. Interference effects have been extensively investigated (B. A. Eriksen & C. W. Eriksen, 1974; Schaffer & LaBerge, 1979; Stroop, 1935; Underwood, 1976). These studies demonstrate that distractors can be analyzed to semantic levels and that the activated internal representations compete with the target for the control of action. Such interference effects demonstrate that selection and response to a
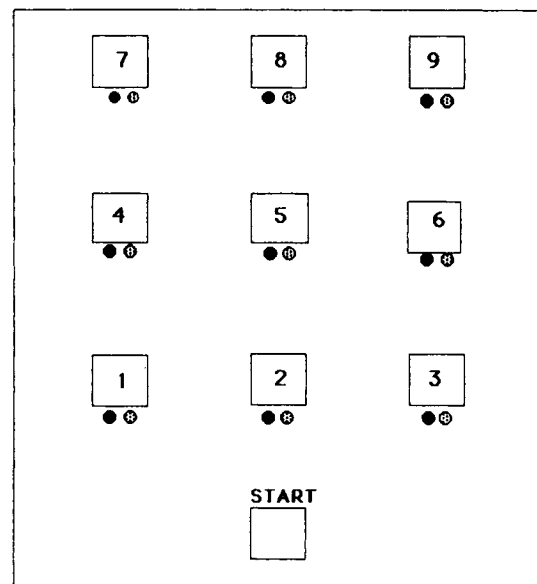

Figure 1. Stimulus board. (Not drawn to scale. The numbers were not actually present.)

target is not a trivial problem for the perception–action system to solve.

We intend to investigate two issues. First and most fundamentally, can interference effects be observed when subjects directly respond to the stimulus, as opposed to the usual arbitrary indirect perception–action couplings? Interference effects have been studied widely and have greatly influenced models of attention, so whether they can be observed in this new task is theoretically important. Second, provided that interference is observed, can the pattern of interference be used to test hypotheses about the internal representations accessed by attentional processes, that is, 2D retina- or 3D viewer-, environment-, or action-centered representations? Our main concern is to compare the interference effects of a distractor when the distractor is closer to the subject than is the target, or vice versa.

In the first experiment, we attempt to distinguish 2D retina- and environment-centered from 3D viewer- and action-centered representations. The models make specific predictions with regard to the pattern of interference produced by the distractor.

Two-dimensional retina-centered representations describe the environment simply in terms of the projections of the stimuli onto the retinal surface. As discussed, distractors closer to the target on the retinal surface produce more interference. In the experiments to be described, distractors that are distant from the subject in 3D space are presented closer to the target in terms of retinal coordinates than are the distractors that are nearer to the subject in 3D space, and therefore asymmetric interference effects should be obtained.[1] More specifically, 2D retinal and 3D spatial information is dissociated. According to the 2D retina-centered view, the far distractor (beyond the target) should produce greater interference than the near distractor.

Environment-centered representations describe the visual scene in terms of the relationships between objects. For example, Button 5 is described in terms of its environmental location in relation to other landmarks in the scene. It is centrally placed among Buttons 2, 4, 6, and 8. Such an environmental description is independent of viewpoint. Thus, even when the viewer moves to a new location, this description does not change. Distractor interference effects produced within this frame of reference should have symmetry. That is, whether a distractor is in front of or behind a target in relation to the viewer should make no difference to the interference produced.

Conversely, 3D viewer-centered models predict an asymmetry. In such models, attention encloses an area from the viewer to the attended stimulus. Thus any distracting stimuli between the viewer and target will fall within this attentional region and hence, we can assume, will receive further analysis and interfere with the target. On the other hand, distractors farther away than the target will fall outside the area of attention and therefore should produce minimal interference. This asymmetric pattern of interference supports the observations of Gawryszewski et al. (1987) and Downing and Pinker (1985). Note that both this and the 2D retina-centered model are viewer centered, but of course the former is based on a 3D frame of reference, whereas the latter is 2D. The

experimental design can distinguish between these models, as they predict opposite asymmetric interference effects.

The action-centered model predicts the same pattern of asymmetry as the 3D viewer-centered model. Interference is predicted to be determined by the relationship between the target and distractor with the hand. In this experiment, the hand's starting position is directly in front of the subject, so there is overlap with the viewpoint. When the distractor is nearer to the hand than to the target, the hand has to pass over the distractor to get to the target. Hence the distractor, which affords a competing response, should cause substantial response competition. Conversely, when the distractor is beyond the target in relation to the hand, the hand can reach the target without going near the distractor, so little competition is expected.

Although the 3D viewer- and action-centered representations cannot be distinguished by the interference effects of front and back distractors, they may be distinguished by examining the effects of distractors on the right and left of the display. Fisk and Goodale (1985) and Prablanc, Echallier, Komilis, and Jeannerod (1979) demonstrated that reaching response is faster to stimuli ipsilateral to the hand. This asymmetry is independent of visual information, as the effects are unaffected by visual fixation. It is unknown whether the interference effects of irrelevant to-be-ignored distractors also produce such an asymmetry. Evidence showing that distractors ipsilateral to the hand produce more interference would support action-centered representations.

Therefore, to summarize our predictions, 2D retina-centered models predict interference asymmetries, such that far distractors produce more interference; environment-centered models predict no interference asymmetries. Alternatively, both 3D viewer- and action-centered models predict asymmetries, such that distractors nearer to the viewer–hand cause more interference. Finally, these latter two frames of reference may be distinguished by left–right asymmetries in interference.

Method

Subjects

Twenty undergraduate students (11 men and 9 women) from an introductory psychology course participated in the experiment for course credit. All subjects were right-handed and had normal color vision.

Apparatus

The subjects viewed a 51 cm × 51 cm board that sat on a table. The far end of the board was raised to an angle of 11° (see Figure 1). On the board were nine 1.5 cm × 1.5 cm buttons arranged in a 3 ×

---

[1] As will be described, the actual distance between the stimuli is equal (13.5 cm). Because of the slope of the board, however, the visual angle between the middle-row target and back-row distractors is less than that between the middle-row target and front-row distractors simply because the former are farther away from the viewer than the latter.

3 matrix with a distance of 13.5 cm separating each row and each column. Two small lights, one red (the target) and one yellow (the distractor), were positioned beside each other directly below each button. The start button was located 13 cm below and directly in line with the first-row center button. The board was interfaced to an Apple IIe computer that controlled light switches and recorded response times and errors.

Only the middle-row targets were intended for analysis, and when a distractor appeared with the target, it was located at one of the adjacent buttons (directly or diagonally in front of or behind the target, or to its left or right on the same row). Therefore, only the visual angles between these buttons are reported.

The visual angles were measured from a constant point in space 34 cm above the table surface and directly in line with the start button. In keeping with the ecological validity of the task. however, subjects' movements were not restricted in any way during the experiment. For example, a previous study found that restricting head movements by using a chin rest impaired pointing accuracy (Biguer, Jeannerod, & Prablanc, 1985). Therefore, the visual angles between subjects and between trials within subjects would have varied some-what: Between Target 5 and distractors directly in front and behind, 17° and 13°, respectively; Target 5 and distractors diagonally in front and behind, 24° and 18°, respectively; Target 5 and distractor on the same row, 16°; Targets 4 and 6 and distractors directly in front and behind, 16° and 12°, respectively; Targets 4 and 6 and distractors diagonally in front and behind, 23° and 19°, respectively; and Targets 4 and 6 and distractor on the same row, 16°.

Design

A one-variable within subjects design was used in which the independent variable was the distractor's location in relation to the target. There were four conditions. The no-distractor (ND) condition, a control condition in which only a target was presented, provided a baseline for measuring distractor interference. In the front-row (FR) distractor condition, the distractor appeared on the front row directly or diagonally in front of the target; these displays included Buttons 4, 4, 5, 5, 5, 6, and 6 for the target and 1, 2, 1, 2, 3, 2, and 3 for the distractor, respectively. In the same-row (SR) distractor condition, the distractor appeared on the same row as the target; displays included Buttons 4, 5, 5, and 6 for the target and 5, 4, 6, and 5 for the distractor, respectively. In the back-row (BR) distractor condition, the distractor appeared on the back row directly or diagonally behind the target; displays included Buttons 4, 4, 5, 5, 5, 6, and 6 for the target and 7, 8, 7, 8, 9, 8 and 9 for the distractor, respectively.

The dependent measure was the response time to depress the target button, signaled by the red light directly below it.

There were 504 trials: 288 were the experimental trials on which the target appeared on one of the middle-row buttons, and 216 were filler trials on which the target appeared on one of the bottom- or top-row buttons. There were 16 experimental trials for each target in the ND condition and 16 for each target–distractor combination in the distractor conditions, with the exception of displays in which the distractor could appear to the left or right of Target 5. In these displays, the distractor appeared to the left of Target 5 on half of the 16 trials and to its right on the other half. Thus there were 48 trials each for Conditions ND and SR and 96 each for Conditions FR and BR; thus each middle-row target appeared 96 times.[2]

On the filler trials, targets were presented on the remaining six buttons (Buttons 1–3 on the bottom row and Buttons 7–9 on the top row). The same experimental conditions were applied to these targets, except that it was impossible for a distractor to appear behind a top-row target or in front of a bottom-row target. Each target on the top and bottom rows appeared 36 times throughout the experiment.

Procedure

The room lights were dimmed to optimize detection of the stimuli. The subjects sat in front of the stimulus board about 27 cm from the near end. They were informed that on each trial a red light would appear at one of the nine buttons and that on some trials a yellow light would also appear but at a different button. They were instructed to depress the red-lit button while ignoring the yellow and to use only their right hand throughout the task. Both speed and accuracy were emphasized. The subjects initiated each trial by depressing the start button. The target and distractor then appeared immediately and remained on until the subject completed the response. Accuracy feedback was provided by a beep from the computer when an error was made. The experiment began with 20 practice trials randomly selected from the 504 experimental and filler trials. Order of presentation of the 504 trials was random, and all randomizations were computer-generated at the start of each session. A 2-min break occurred halfway through the session, which lasted approximately 30 min. The experimenter remained in the room throughout the session to ensure that subjects performed the task with their right hand only.

Results and Discussion

Given the simplicity of the task, subjects who did not achieve a 95% accuracy level in any condition (applied prior to collapsing FR and BR in all experiments) were dropped and replaced with new subjects. On the basis of this criterion, 1 subject who made four errors in one condition (SR) was replaced.

Omitting error trials, we computed median response times for each subject in each condition and submitted them to a repeated measures analysis of variance (ANOVA) (see Table 1).[3] We calculated interference by subtracting the mean median response time in the ND condition from each distractor condition. These difference scores are presented in Figure 2A. As is evident, there were large differences in response times as a function of distractor location, $F(3, 57) = 24.92$, $MS_e = 106.74$, $p < .0001$. In particular, front-row distractors appeared to cause more interference than back-row distractors, whereas distractors on the same row as the target caused an intermediate level of interference. Multiple comparisons (through Tukey's honestly significant difference test in all experiments) confirmed that FR differed reliably from ND, BR, and SR ($p < .01$). SR also differed reliably from ND ($p < .01$), but BR did not. Thus distractors on the front row, nearer the viewer–hand, caused more interference than distractors beyond and on the same row as the target.

---

[2] Initial data analysis of FR and BR was in terms of whether the distractors were directly or diagonally in front of or behind the target. This analysis showed no significant differences between distractors diagonally in front versus directly in front or between distractors diagonally behind versus directly behind the target. Therefore, as the most theoretically important contrasts were whether the distractor was simply in front of or behind the target, for parsimony and ease of discourse the conditions directly and diagonally in front of and behind the target were collapsed.

[3] Analysis by Miller (1988) shows that for large numbers of trials, differences in the numbers between conditions (48 in ND and SR and 96 in BR and FR) has no impact on the medians obtained.

Table 1

Response Times (RTs, in Milliseconds) and Percentage Error Rates as a Function of Distractor Condition

	ND		FR		SR		BR	
Experiment	RT	% error	RT	% error	RT	% error	RT	% error
1	606	0.7	633	0.5	620	0.2	614	0.6
2								
Hand at bottom	628	0.5	651	0.7	641	0.0	632	0.7
Hand at top	564	0.8	566	0.9	588	1.5	591	0.8
3	636	0.6	660	0.5	647	0.3	643	0.7
4								
Hand at bottom	697	0.1	726	1.3	722	1.2	697	0.8
Hand at top	617	0.2	635	1.0	641	1.0	651	0.8
5								
Hand at bottom	602	0.4	619	0.4	—	—	598	0.3
Hand at top	590	1.0	598	0.2	—	—	606	0.5

Note. ND denotes the no-distractor condition, FR denotes the front-row distractor condition, SR denotes the same-row distractor condition, and BR denotes the back-row distractor condition.

This asymmetry of interference effects provides support for the viewer- and action-centered models, but it does not distinguish between these models. To support an action-centered model, it is necessary to find evidence for an asymmetry in interference effects that is determined by the hand responding to the target and not by visual information. Research by Fisk and Goodale (1985) and Prablanc et al. (1979) suggests where this asymmetry may be observed. They demonstrated that responses to targets to the right of midline were completed faster than responses to targets to the left when the right hand was used. This effect was independent of visual information, which was manipulated by locus of fixation. Analysis of our
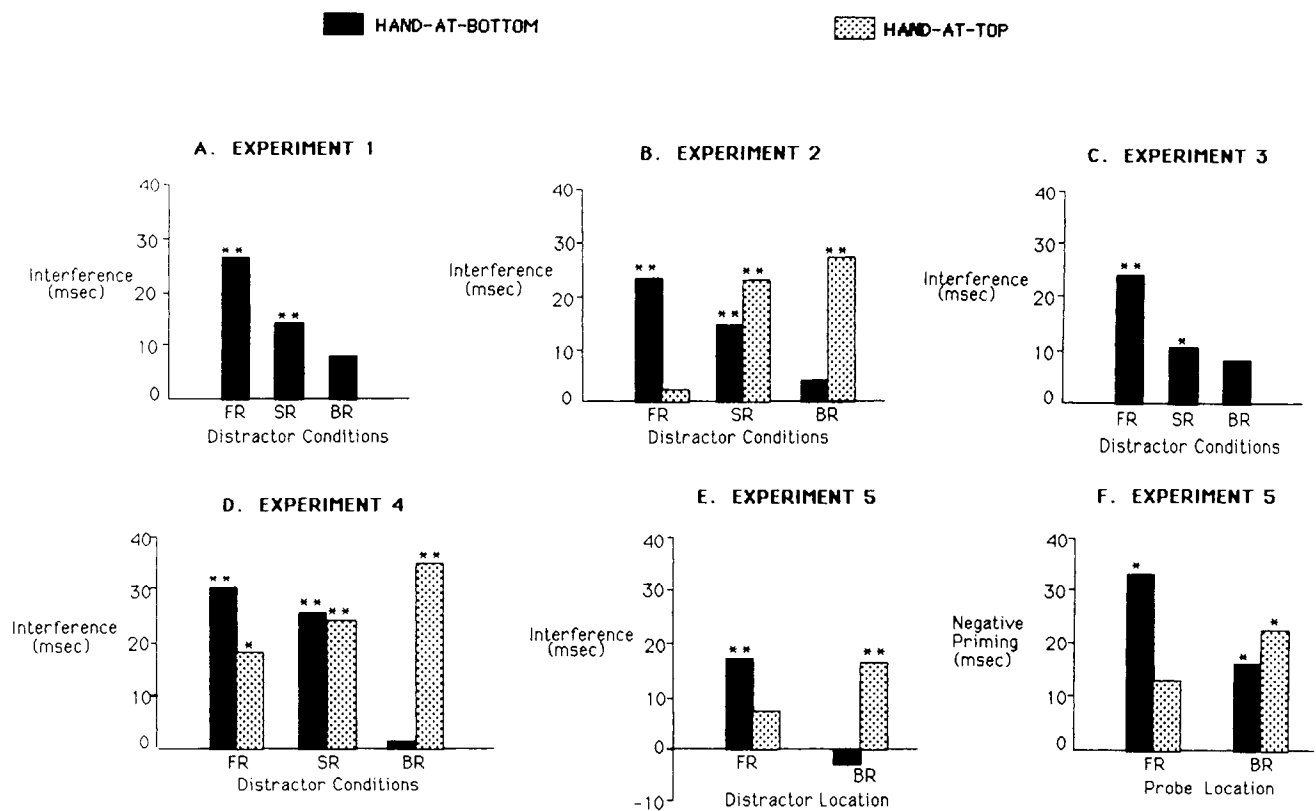

Figure 2. Interference and negative priming effects in Experiments 1–5. (FR denotes front row, SR denotes same row, and BR denotes back row. *p = .05. **p = .01.)

Table 2

Response Times (RTs, in Milliseconds) and Percentage Error Rates for Target 5 as a Function of Distractor Condition

Experiment	ND		Left distractor		Right distractor	
	RT	% error	RT	% error	RT	% error
1	588	0.9	608	2.5	624	2.5
2						
Hand at bottom	619	1.3	626	2.5	645	2.5
Hand at top	532	2.2	562	5.0	556	2.5
3	607	0.3	647	0.0	610	1.3

Note. ND denotes the no-distractor condition.

data supports their observations. The mean median response time to Target 4 on the left (657 ms) was significantly longer than to Target 6 on the right (607 ms), $F(1, 19) = 128.65$, $MS_e = 198.87$, $p < .0001$.

If interference effects produced by irrelevant to-be-ignored distractors also show this left–right asymmetry, this would provide some initial support for action-centered representations. We performed an ANOVA on subjects' responses to the central target (Target 5) under these conditions: (a) when the target was presented alone (ND), (b) when a distractor was presented at Location 1, diagonally in front of the target and to the left of midline, and (c) when the distractor was presented at Location 3, diagonally in front of the target and to the right of midline. There was a significant effect of distractor condition, $F(2, 38) = 7.20$, $MS_e = 868.55$, $p < .01$. As the data in Table 2 indicate, interference effects were greater for Distractor 3 on the right. Only this distractor differed significantly from ND ($p < .01$) in the multiple comparisons.

These interference effects discount a retina-centered model, as far distractors were closer to the target in terms of retinal coordinates than were near distractors, but they produced smaller interference effects. Environment-centered representations cannot account for the larger interference effects produced by front distractors in relation to back distractors. Finally, a 3D viewer-centered model cannot easily explain why distractors on the right cause more interference than those on the left. This left–right asymmetry is investigated further in Experiment 3. First, however, we use another experimental manipulation in an attempt to demonstrate that the attentional interference effects are determined by action rather than by visual representations.

Experiment 2

In Experiment 1, the starting position of the hand was directly in front of the subject. Thus, distractors on the front row, which caused the most interference, were not only between the target and the subject but between the target and the subject's hand as well. As a result, both the viewer- and action-centered models could easily account for the observed asymmetry in interference between front and back distractors. One way to disentangle the predictions of the two models was to move the starting position of the hand without changing the subject's viewpoint. This was accomplished by turning

the stimulus board around so that the start button was located at the top of the board. In this version of the task, front-row distractors are still between the target and the subject but are beyond the target in relation to the subject's hand. Thus, Experiment 2 evaluates the remaining hypotheses under two main testing conditions: one with the starting position of the hand at the bottom of the board as in Experiment 1 and the other with the starting position of the hand at the top of the board. If attention accesses viewer-centered coordinates, front-row distractors should cause the most interference regardless of the starting position of the hand. Alternatively, if attention accesses action-centered coordinates, then an interaction between hand position and distractor location should be observed. Front-row distractors should cause more interference when the hand starts at the bottom of the board, but the interference should shift to the back-row distractors when the hand starts at the top of the board.

Method

Subjects

Twenty subjects (12 women and 8 men) were recruited from the same subject pool used in Experiment 1 and assigned to the condition in which the starting position of the hand was at the bottom of the board (hand at bottom). There was one constraint placed on performance of the task when the starting position of the hand was at the top of the board (hand at top), namely that subjects were able to depress the start button in such a way as not to obstruct their view of the nine stimulus buttons with their arm. Test runs in this condition revealed that only tall subjects (more precisely, long-armed subjects) could perform the task without too much difficulty. Consequently, the one restriction placed on the selection of subjects for this condition was that they be at least 5'10" (1.78 m) in height. Twenty subjects (17 men and 3 women) from the same subject pool as the first condition participated. All 40 subjects were right-handed and had normal color vision.

Apparatus and Stimuli

The same apparatus was used as in Experiment 1. To facilitate performance of the task in the hand-at-top condition, the distance between the subjects and the start button was shortened by raising the board to an angle of 35° from the table. For consistency, this angle was maintained for subjects starting at the bottom. In the hand-at-bottom condition, the visual angles were as follows: between Target 5 and distractors directly in front and behind, 22° and 17°, respectively; Target 5 and distractors diagonally in front and behind, 32° and 23°, respectively; Target 5 and distractor on the same row, 20°; Targets 4 and 6 and distractors directly in front and behind, 20° and 16°, respectively; Targets 4 and 6 and distractors diagonally in front and behind, 29° and 25°, respectively; Targets 4 and 6 and distractor on the same row, 20°. Turning the board around in the hand-at-top condition lowered each row of stimulus buttons so that these visual angles were slightly larger than those in the hand-at-bottom condition: between Target 5 and distractors directly in front and behind, 28° and 22°, respectively; Target 5 and distractors diagonally in front and behind, 40° and 29°, respectively; Target 5 and distractor on the same row, 24°; Targets 4 and 6 and distractors directly in front and behind, 24° and 20°, respectively; Targets 4 and 6 and distractors diagonally in front and behind, 34° and 32°, respectively; Targets 4 and 6 and distractor on the same row, 24°.

Design and Procedure

The design of the experiment was a 2 × 4 mixed factorial with starting position of the hand (bottom vs. top) as the between-subjects variable and distractor location (ND, FR, SR, or BR) as the within-subjects variable. Note that the distractor conditions still describe the target-distractor relationship from the viewpoint of the subject. For example, FR relates to all distractors on the row nearest the subject (e.g., Target 4 and Distractor 1 or 2), whereas BR relates to all distractors on the row farthest from the subject (e.g., Target 4 and Distractor 7 or 8).

The number of trials in each distractor condition and all aspects of the procedure were the same as in Experiment 1.

Results and Discussion

Four of the 40 subjects had to be replaced because of high error rates. In the hand-at-bottom condition, 1 subject made four errors in Condition FR, and 1 made at least four errors in each of Conditions FR and BR. In the hand-at-top condition, 1 subject made at least four errors in each of Conditions FR, BR, and SR, and 1 subject made more than four errors in Condition SR.

For each subject in each hand condition, we calculated median response times for correct trials for each distractor condition and submitted them to a mixed-design ANOVA. There was a significant main effect of hand position, $F(1, 38)$ = 9.65, MS_e = 15,244, $p < .01$. As is evident in the data presented in Table 1, response times for the hand-at-top condition were consistently lower than response times for the hand-at-bottom condition. This result is consistent with a previously reported finding that backward movements are initiated faster than forward movements (Rosenbaum, 1980). There was also an interaction between hand position and distractor location, $F(3, 114)$ = 23.34, MS_e = 149.25, $p < .0001$. As the interference scores in Figure 2B clearly indicate, there was a complete reversal in the pattern of interference between hand positions. When the starting position of the hand was at the bottom of the board, front-row distractors caused more interference than back-row distractors, replicating Experiment 1. When the hand started at the top of the board, however, interference shifted to the back-row distractors.

To confirm the significance of the shift in interference, we performed ANOVAs separately on each hand position. Both analyses revealed highly significant effects of distractor, $F(3, 57)$ = 26.44, MS_e = 81.62, $p < .0001$, for the hand-at-bottom condition, and $F(3, 57)$ = 18.27, MS_e = 216.88, $p < .0001$, for the hand-at-top condition. Multiple comparisons established that both FR and SR differed reliably from ND and from BR ($p < .01$), and FR differed from SR ($p < .01$) when the hand started at the bottom of the board. In the hand-at-top comparisons, BR and SR differed reliably from ND and from FR ($p < .01$).

Also evident in the hand-at-bottom condition of this experiment were the right-side biases observed in Experiment 1. The mean median response time to Target 4 (681 ms) was significantly higher than to Target 6 (620 ms), $F(1, 19)$ = 139.35, MS_e = 264.28, $p < .0001$. There was a significant effect of distractor condition in the separate analysis of Target 5, $F(2, 38)$ = 5.07, MS_e = 700.46, $p < .05$. As revealed by the

multiple comparisons, the distractor diagonally in front and to the right of Target 5 differed reliably from ND ($p < .05$), whereas the distractor diagonally in front and to the left did not (see Table 2). These effects failed to emerge in the hand-at-top analysis probably because stimuli on the right side were sometimes blocked from view by the subject's arms when he or she was reaching for the start button at the top of the board. This is suggested in a shift in distractor interference to the left side of the board as the data in Table 2 indicate. The ANOVA on Target 5 in this hand condition revealed a significant effect of distractor condition, $F(2, 38)$ = 4.11, MS_e = 1,248, $p < .05$. The multiple comparisons, however, showed that the distractor diagonally behind and to the left of Target 5 differed significantly from ND ($p < .05$), whereas the distractor diagonally behind and to the right did not. There was no significant difference, however, in the response times to Targets 4 (598 ms) and 6 (607 ms) in this hand condition.

Overall, the results of this experiment, which reveal both a shift in the interference pattern to back-row distractors when the hand started at the top of the board and a replication of the right-side biases (in the hand-at-bottom condition) observed in Experiment 1, suggest that attention accesses action-centered representations in a reaching task.

Experiment 3

The purpose of this experiment was to investigate further the right-side interference effect observed in the first two experiments. In one respect, it is possible that right-handed people simply show an attentional bias for stimuli presented in the right hemispace. An alternative possibility, however, relates more directly to the action-centered hypothesis. Specifically, if attention accesses action-centered representations, then it may be biased to the side of the responding hand. Therefore, if subjects respond with their left hands rather than their right hands, distractors on the left should interfere more than distractors on the right. Such a shift in the attentional bias would be very difficult to account for in terms of a viewer-centered model because the visual perspective of the stimulus board is identical in both Experiment 2 and the present experiment.

Method

Subjects

The subjects were 20 right-handed undergraduates (10 men and 10 women) from an introductory psychology course who participated in fulfillment of course requirements.

Design and Procedure

All aspects of the design and procedure were identical to those of the hand-at-bottom condition in Experiment 2 except that subjects responded with their left hands.

Results and Discussion

One subject was dropped because of a high error rate (eight errors in Condition FR). To examine the overall interference

pattern, we performed an ANOVA on the median response times for each condition (see Table 1). Again, there was a highly significant effect of condition, $F(3, 57) = 18.80$, $MS_e = 111.25$, $p < .0001$. As the interference data in Figure 2C indicate, distractors on the front row caused more interference than distractors on the back row, replicating the effects observed in Experiment 1 and in the hand-at-bottom condition of Experiment 2. Multiple comparisons confirmed reliable differences between FR and ND, BR, and SR ($p < .01$) and between SR and ND ($p < .05$).

In examining the left–right side bias, analysis of the mean median response times to Targets 4 and 6 revealed an effect in the opposite direction of that observed in the earlier experiments. This time, the mean response time to Target 4 (623 ms) was faster than to Target 6 (710 ms), $F(1, 19) = 170.16$, $MS_e = 446.47$, $p < .0001$.

To examine the left–right side effect of distractors, we performed a between-experiments comparison on Target 5 with the left- and right-side distractors on the front row by using the response time data from this experiment and the hand-at-bottom condition of Experiment 2 (see Table 2). The result of this analysis was a highly significant interaction of experiment with distractor condition, $F(2, 76) = 9.93$, $MS_e = 772.85$, $p < .001$. Analysis of Target 5 in the present experiment revealed a significant effect of distractor condition, $F(2, 38) = 11.56$, $MS_e = 845.24$, $p < .001$. In the multiple comparisons, significant differences were observed between ND and the distractor diagonally in front and to the left of Target 5 ($p < .01$) and between the left and right distractors ($p < .01$). The ND and the distractor diagonally in front and to the right of the target did not differ.

The left–right asymmetries in interference effects provide support for prior interpretations of such effects. Fisk and Goodale (1985) demonstrated that faster responses to targets ipsilateral to the hand are due to body frame of reference rather than visual information. They further suggested that such asymmetries cannot simply be accounted for in terms of peripheral mechanical constraints of the shoulder skeletal-muscular system. In addition, Georgopoulos, Kalaska, and Massey (1981) discovered that responses of cells in the motor cortex were directionally specific. Of most pertinence, the cells had preference to ipsilateral movements forward and lateral from the body axis (in our studies, this is equivalent to Target 4 when responding with the left hand and Target 6 when responding with the right hand). That is, the results reflect different neural programming of reaches, prior to actual mechanical movements. The fact that the interfering effects of irrelevant to-be-ignored distractors produce the same result also discounts peripheral mechanical explanations simply because no movement is actually made toward the distractor stimulus. Therefore, this experiment further demonstrates the action-centered nature of the internal representations accessed by attention in this task.

Experiment 4

Although the results of the last two experiments favor the action-centered hypothesis, there is an alternative retina-centered explanation for the results of Experiment 2 that must be considered before firm conclusions can be made. If subjects

visually fixated the start button at the beginning of each trial, it could be argued that back-row distractors in the hand-at-top condition were perceptually more salient because of their nearness to the fovea in comparison to front-row distractors. Bartz (1966) and Prablanc et al. (1979) clearly demonstrated that fixations of targets precede completion of the reaching response. In the current task of reaching to a target and then returning to start position, fixation may have moved between the starting position and the target. The same argument holds when the hand is at the bottom of the board. That is, when fixating the start position, front-row distractors are close to the fovea. Interference asymmetries could therefore be accounted for by retina-centered coordinates.

The goal of the present experiment was to eliminate this possible confound by ensuring that fixation was directed toward the center of the display when the target and distractor stimuli were presented.

Method

Subjects

For the testing condition with the hand starting at the bottom of the board, 20 undergraduate and graduate students (15 women and 5 men) were paid $5 for participating. The same criteria used in Experiment 2 were placed on the selection of subjects for the hand-at-top condition. Twenty subjects (17 men and 3 women) from a second-year psychology course participated for course credit.

Apparatus and Stimuli

The setup of the stimulus board was identical to that of Experiment 2. The only change in the stimuli was that a target could be red or yellow on each trial.

Design and Procedure

The design was the same as Experiment 2, with hand position (top vs. bottom) as the between-subjects variable and distractor location as the within-subjects variable. The number of trials for each condition (ND, FR, BR, or SR) also remained the same. The target was red on half of the trials in each condition and yellow on the other half. The events making up a trial varied from Experiment 2 in the following way. Approximately 1 s after the start button was depressed, a red or yellow light appeared on Button 5, cuing the target color for that trial. The exposure duration of the cue was 27 ms. Between cue offset and target–distractor onset there was a time interval of 250 ms to allow processing of the cue without disruption from other stimulus events. Failure to fixate the center button would cause subjects to miss the color cue, resulting in a correct response by chance only. This was confirmed in a pilot study in which the subjects were required to maintain fixation at the start button until cue offset. The results of this study, which was based on 4 subjects, were mean error rates of 2% in ND, 56% in FR, 49% in SR, and 20% in BR. The low error rate in BR, as suggested by subjects' reports, probably reflects a tendency to respond to the nearest stimulus when the alternate choice is a back-row stimulus far from the subject's hand.

The procedure varied only with regard to the instructions. Subjects were told that the target could be either red or yellow on each trial and that the cue to the color would flash very briefly on Button 5 after the start button was pressed. Subjects were warned that if they were not fixating Button 5 when the start button was pressed, they

would miss the cue and as a result have to guess which light was the target on that trial. To maintain the respective starting positions, subjects were asked to hold down the start key until the cue had been presented. The experimenter remained in the room for the duration of the session to ensure that they performed the task accordingly.

Results and Discussion

Thirteen subjects had to be replaced because of high error rates (4 subjects in the hand-at-bottom condition and 9 subjects in the hand-at-top condition). This high replacement rate reflects the greater difficulty of this version of the task compared with the previous ones. Subjects not only had to process information regarding the color of the target but had to retain it in the presence of conflicting information when the target and distractor were presented. The criteria could have been lowered to match the level of difficulty; however, it was possible that a high proportion of errors were due to failure to fixate the center button. Had this been the case, a large number of correct "guess" trials would have been retained for analysis, and because fixation was a critical factor in this experiment, a strict error criterion was necessary.

We submitted the median response times for correct trials for each subject in each condition to a mixed-design ANOVA as in Experiment 2. Replicating the first result of Experiment 2 was a main effect of hand position, $F(1, 38) = 5.46, MS_e = 40,541, p < .03$. As the data in Table 1 indicate, response times were again consistently lower in the hand-at-top condition. The critical result, however, was a replication of the interaction between hand position and distractor location, $F(3, 114) = 9.36, MS_e = 419.99, p < .001$.

Separate ANOVAs on each hand-testing condition revealed significant effects of distractor in each case, $F(3, 57) = 13.90, MS_e = 361.94, p < .0001$, for the hand-at-bottom condition, and $F(3, 57) = 8.69, MS_e = 478.04, p < .001$, for the hand-at-top condition. The interference scores presented in Figure 1D indicate a replication of the asymmetries observed in Experiment 2. Multiple comparisons confirmed reliable differences between FR and SR and ND and BR ($p < .01$) in the hand-at-bottom condition and between BR–SR and ND ($p < .01$) in the hand-at-top condition. One inconsistency was noted in the hand-at-top condition: a reliable difference between ND and FR, although it was significant at the .05 level only.

A comparison of Figures 1B and 1D suggests that the shift in the interference pattern to the back-row distractors in the hand-at-top testing condition was not as clear-cut as that observed in Experiment 2. It is possible that although subjects were periodically reminded throughout the experiment to keep their hand on the start button until the color cue appeared, they may have moved their hand away from the start button on some trials. Nevertheless, the shift in interference to the back-row distractors was still largely evident in this experiment and was confirmed by the interaction between hand positions. This result is completely incompatible with the alternative retina-centered explanation. Thus, even with visual fixation at the center of the board, distractors nearest the hand still caused the most interference, as the action-centered model predicted.

Experiment 5

The first four experiments evaluated the predictions of the alternative hypotheses within an interference paradigm and produced results that were problematic for all but the action-centered model. In the present experiment, we investigate another testable aspect of the model, namely its predictions within a negative priming paradigm.

Selective attention has been characterized as a twofold process involving both excitatory and inhibitory components acting on the internal representations of attended and ignored objects, respectively. This view has been supported by findings of a negative priming effect on responses to targets that are identical or semantically related to the distractor in the preceding trial. For example, subjects take longer to identify a picture of a dog if a picture of a cat was the ignored object in the preceding trial than if, for example, the ignored object was a flute (Tipper, 1985). The logic underlying the paradigm is that if a distractor is inhibited during selection of the target, then on the next trial if processing of the target requires access to the same or related inhibited representations, response to that target is slower. The effect has been demonstrated in a spatial task. When subjects are required to report the location of a target in a 2D display, responses are slower when the target appears in the same location as the distractor in the preceding trial in relation to trials in which the distractor appears in a neutral location (Tipper, Brehaut, & Driver, 1990). This latter finding in particular suggests the suitability of the paradigm for investigating inhibition mechanisms in the present 3D spatial task.

According to the action-centered hypothesis, attention accesses a reference frame of internal representations whereby objects' locations are defined in relation to the position of the hand. As a consequence, distractors nearer the hand should compete more strongly for response than distractors farther from the hand. If this is correct, then it is reasonable to assume that more inhibition would have to be placed on the internal representations of distractors near the hand than on distractors far from the hand. Therefore, near-hand distractors would be expected to produce large negative priming effects on responses to targets subsequently presented at their locations, whereas distractors far from the hand would be expected to produce little or no negative priming effects on responses to targets subsequently appearing at the same locations. Thus the action-centered hypothesis predicts asymmetries in negative priming effects that will correspond to the asymmetries observed with the interference effects. Specifically, larger negative priming effects should be observed on front-row targets compared with back-row targets when the hand starts at the bottom of the board, shifting to larger negative priming effects on the back-row targets when the hand starts at the top of the board.

Method

Subjects

The subjects were 40 undergraduates (24 men and 16 women) from first- and second-year psychology courses who participated in the experiment for course credit. Half of the subjects performed the

task with the hand starting at the bottom of the board, and the other half (tall subjects) performed the task with the hand starting at the top of the board.

Apparatus

The setup of the stimulus board was identical to that of Experiment 2 for each hand condition. The target was red on every trial.

Design

We took measurements of both interference and negative priming. To measure interference, we used a 2 × 3 mixed design in which testing condition (hand starting at bottom vs. top) was the between-

Figure 3. Examples of prime–probe displays used in Experiment 5. (IR denotes ignored repetition, T denotes target, and D denotes distractor.)

subjects variable and distractor location (ND, FR, or BR) was the within-subjects variable. (SR was excluded to cut down on the number of trials.)

To measure negative priming, we used a three-variable mixed design in which testing condition was again the between-subjects variable. Negative priming measures were obtained from the two within-subjects variables. There were two trial types: a prime followed by a probe. The first within-subjects variable was the target's location on the probe trial: front row or back row. The second within-subjects variable was the distractor's location on the prime trial: same or different location in relation to the probe target. These conditions are described in detail as follows.

Front—ignored repetition (front-IR). The probe target appeared on the front row (Buttons 1, 2, or 3) in the same location as the distractor in the preceding prime. Probe displays included Buttons 1, 2, 2, and 3 for the target and 2, 1, 3, and 2 for the distractor, respectively. Each of these displays followed a prime display in which the distractor appeared in front of the target from the subject's viewpoint. For example, Prime Display 4–1 (target–distractor buttons) preceded Probe Display 1–2 (see Figure 3A).

Front—control. This condition provided a baseline measure of response times to the aforementioned probe displays. It differed from front-IR only in the prime displays that preceded the probes. The prime distractor appeared on the front row but in a different location from the probe target. For example, Prime Display 6–3 preceded Probe Display 1–2 (see Figure 3B).

Back—ignored repetition (back-IR). This condition was identical to front-IR except that the probe targets appeared on the back row and followed a prime display in which the distractor appeared behind the target from the subject's viewpoint.

Probe displays included Buttons 7, 8, 8, and 9 for the target and 8, 7, 9, and 8 for the distractor. For example, Prime Display 4–7 preceded Probe Display 7–8 (see Figure 3C).

Back—control. This condition was identical to front–control with the exception again being the back-row location of the prime distractors and probe targets. Probe displays were identical to those in back-IR; only the prime displays differed. For example, Prime Display 6–9 preceded Probe Display 7–8 (see Figure 3D).

Note that the probe distractors always appeared on the same row as the target. This was done to maintain the same level of distractor interference on the probes between hand conditions. For example, a distractor appearing behind a front-row probe target would have been farther from the hand in the hand-at-bottom condition but nearer the hand in the hand-at-top condition. Thus by presenting distractors on the same row as the probe target, the risk of confounding negative priming with distractor interference between hand conditions was avoided.

There were 48 trials for each of the four probe conditions, giving 192 probe trials in each hand condition. With the front-IR condition as an example, these trials were partitioned as follows: 16 trials for Display 1–2, 16 trials for Display 3–2, 8 trials for Display 2–1, and 8 trials for Display 2–3.

Response times to targets on the 192 prime trials plus an additional 88 trials provided the measures of performance in the FR and BR interference conditions. Interference trials consisted of 14 possible target–distractor combinations: Target 4 with Distractors 1,2,7, and 8; Target 5 with Distractors 1,2,3,7,8, and 9; Target 6 with Distractors 2,3,8, and 9. Each combination was presented 20 times, resulting in 140 trials each for Conditions FR and BR. The ND condition consisted of 16 trials of each middle-row target presented by itself for 48 trials in this condition. Finally, there were 120 filler trials on which targets were presented on the front row with a distractor behind it and on the back row with a distractor in front of it. This brought the number of trials for the experiment to 640 (plus 20 practice).

The 192 prime–probe pairs plus the additional 88 interference trials and the 120 fillers were presented randomly. Mixing the last
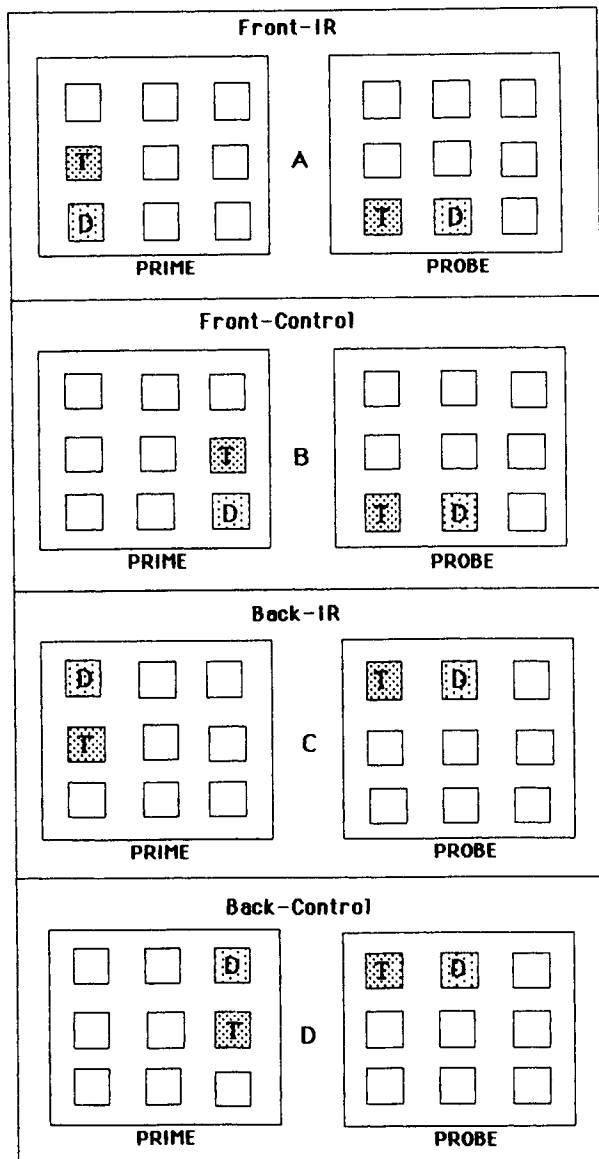
two trial types with the prime–probe pairs served to prevent subjects from becoming aware of a relationship between pairs of trials.

All trial types considered, a target appeared on each of the bottom-and top-row buttons 52 times, on Buttons 4 and 6 on the middle row 96 times, and on Button 5 on the middle row 136 times. There were 56 trials in which a distractor appeared on Buttons 1,3,7, and 9; 124 trials on Buttons 2 and 8; 30 trials on Buttons 4 and 6; and 60 trials on Button 5.

Procedure

The procedure was as in Experiment 2.

Results and Discussion

Interference

Omitting error trials, we submitted the median response times from the primes and the additional interference trials for each subject in each hand and distractor condition to a 2 × 3 mixed-variable ANOVA (see Table 1). This analysis revealed a highly significant interaction between hand position and distractor location, $F(2, 76) = 16.94$, $MS_e = 128.82$, $p < .0001$. As is evident in the interference data presented in Figure 1E, when the hand started at the bottom of the board, front-row distractors caused greater interference than back-row distractors, whereas the interference shifted to the back-row distractors when the hand started at the top of the board. Analyses performed separately on each hand condition revealed significant effects of distractor location in both cases: In the hand-at-bottom condition, $F(2, 38) = 22.31$, $MS_e = 106.65$, $p < .0001$; in the hand-at-top condition, $F(2, 38) = 8.45$, $MS_e = 150.99$, $p < .002$. Multiple comparisons confirmed reliable differences between FR and ND–BR in the hand-at-bottom condition ($p < .01$) and between BR and ND in the hand-at-top condition ($p < .01$). Thus, the interference patterns of the previous experiments were replicated.

Negative Priming

For each subject in each hand condition, we computed the median response times for correct trials for the IR and control conditions for both front- and back-row targets and submitted them to a three-variable mixed ANOVA (see Table 3). Hand position was the between-subjects variable, and probe target location (front row vs. back row) and negative priming (IR vs. control) were within-subjects variables. This analysis revealed a significant three-way Hand × Target Row × Negative Priming interaction, $F(1, 38) = 8.48$, $MS_e = 215.35$, $p < .01$. We obtained negative priming scores by subtracting each

Table 3
Response Times (RTs, in Milliseconds) and Percentage Error Rates on Probe Trials in Experiment 5

	Front–IR		Front–control		Back–IR		Back–control	
Condition	RT	% error	RT	% error	RT	% error	RT	% error
Hand at bottom	618	0.3	585	0.5	714	0.1	698	0.1
Hand at top	739	0.8	727	0.6	617	0.2	596	0.2

Note. IR denotes ignored repetition.

control condition from each IR condition (see Figure 2F). As suggested by these data, negative priming effects were greater on front-row targets compared with back-row targets when the hand started at the bottom of the board and greater on back-row targets compared with front-row targets when the hand started at the top of the board. To determine if negative priming between front- and back-row targets interacted within each testing condition, we performed two-variable ANOVAs separately on each hand condition with repeated measures on target row and negative priming.

Negative priming did interact with target row in the hand-at-bottom condition, $F(1, 19) = 12.53$, $MS_e = 125.08$, $p < .01$, but not in the hand-at-top condition, $F(1, 19) = 1.44$, $MS_e = 303.47$. Scheffe tests on the negative priming effects on each target row in each hand condition revealed significant effects on both front- and back-row targets in the hand-at-bottom condition: For the front-row targets, $F(1, 19) = 90.53$, $MS_e = 125.08$, $p < .01$; for the back-row targets, $F(1, 19) = 20.21$, $MS_e = 125.08$, $p < .05$. In the hand-at-top condition, the negative priming effect on back-row targets was significant, $F(1, 19) = 15.73$, $MS_e = 303.47$, $p < .05$, but it failed to reach significance on the front-row targets, $F(1, 19) = 5.19$, $MS_e = 303.47$. This latter result suggests that the negative priming pattern did shift in the hand-at-top condition despite the failure to observe an interaction between target row and negative priming in the two-way analysis of this condition.

The asymmetric patterns of negative priming observed in this experiment suggest that a higher level of inhibition was placed on the internal representations of distractor objects between the hand and the target than on distractors farther from the hand. Thus, these results, converging with the interference findings of the previous experiments, provide strong support for an action-centered model of attention.

General Discussion

Models of attention are constrained by empirical observations. Therefore, it is important to consider carefully the experimental techniques used. It was stressed previously that current models of attention are determined predominantly by experiments that briefly present static 2D displays and require arbitrary responses. It is clear that such experimental situations are rarely encountered in our usual interactions with the environment.

As Marr (1982) stressed, a computational level of analysis is necessary. Such an analysis specifies for what functions a particular system has evolved: It considers biological goals and the environment in which such goals are to be achieved. Considerations at a computational level make clear what has to be explained; fortunately, they also identify constraints, both evolutionary and environmental, that have determined the system under study and assist in its understanding.

Such a perspective motivated the current studies. Could the empirical observations of traditional experimental procedures also be observed in a situation that was somewhat closer to interactions with the 3D environment? Fortunately, our results provide an affirmative answer to this question: Both interference and negative priming were obtained when subjects were required to respond directly to stimuli in 3D space.

We also considered the form of internal representation that was accessed by selective attention mechanisms during such a task. Four alternatives, encompassing the major forms of representation from perceptual input to response output, were considered: 2D retina-, 3D viewer-, environment-, and action-centered representations. Three experimental results (front–back interference, negative priming asymmetries, and left–right interference asymmetries) have provided converging evidence suggesting that when actions are aimed directly at objects in 3D environments, attention accesses the latter action-centered representation. Such results highlight the importance of the perception–action system: Perception evolved specifically to enable organisms to act successfully on their environments, and hence any study of perception should consider the action goals of the experiment.

In addition, the relationship between perception and action has been emphasized in neurophysiological studies. Subcortical systems are involved when reaching toward objects (D. R. Humphrey, 1979). Of particular relevance to the current data is Sparks's (1988) argument that sensory and motor maps in the superior colliculus are closely linked. In fact, sensory maps are encoded in motor (not sensory) coordinates such that as an animal changes body position, the maps of sensory space are dynamically changed.

At the cortical level, Rizzolatti, Gentilucci, and Matelli (1985) distinguished between space around the body (peripersonal space) that represents information necessary for reaching and space distant from the body. They suggested that the former is represented in the postarcuate cortex (Area 6) and the inferior and posterior parietal lobes (Area 7). For example, Jeannerod (1986) reported cases of optic ataxia in which lesions to the posterior parietal cortex result in failures to direct the hand toward targets. He suggested that hand–target relationships can no longer be transferred between visual and proprioceptive maps (see also Jones & Powell, 1970). Furthermore, Rizzolatti, Riggio, Dascola, and Umilta (1987) proposed that attention accesses these representations of peripersonal space—a premotor theory of attention. More specifically, they disagreed with the usual notion that attention simply moves through visual space; rather, attention can depend on motor programs that compute target location in external space for the effector systems.

We suggest that the motor programs in our current experiments specify the reaching response to the target; however, motor programs for the distractor are also specified in parallel. Goldberg and Segraves (1987) provided evidence that the brain can indeed have multiple simultaneous conflicting motor signals. They further suggest that the frontal cortex is probably important in selecting which motor signals evoke movements necessary to achieve current purposes (see also Fuster, 1980).

Analysis of everyday slips of actions in human subjects arrives at strikingly similar conclusions. Norman (1981) suggested that such failures of action are produced when there are several competing actions, that is, a failure of action selection when, for example, hot water is poured into a cup rather than a teapot. Furthermore, Coles, Gratton, Bashore, C. W. Eriksen, and Donchin (1985) and C. W. Eriksen, Coles, Morris, and O'Hara (1985) demonstrated electromyographic

activity in the hand that is associated with response to the irrelevant distracting object, which strongly suggests the potential for competition between action representations.

The present results suggest two further pieces of information. First, the nature of the simultaneously activated responses determines the level of competition (interference) between them. Distractors that initiate responses that are within the path of the response to the target cause substantial competition; those beyond the target do not, and distractors ipsilateral to the responding hand produce more interference. Second, when the hand passes over or past a distractor on its way to the target, the response evoked by the distractor is actively inhibited. Many further questions remain that we intend to pursue. For example, action can be fractionated into many components, such as premotor preparation, ballistic acceleration movement, and subsequent fine motor adjustments during deceleration (Jeannerod, 1988). At what stage is interference and selective inhibition taking place?

Finally, our current observations, which suggest that attention accesses action-centered representations, contradict previous work (Tipper & Driver, 1988; Tipper, MacQueen, & Brehaut, 1988). This previous research attempted to identify where selective inhibition was located in the series of processes from retinal input to response output. The conclusion drawn from these studies was that inhibition was not associated either with early perceptual analysis of features, as the effect transferred between stimuli with no features in common (pictures and words), or with specific motor responses, as the effect transferred between different response systems (verbal and manual).

It is sometimes suggested that inhibition of distractor representations can be equated with the operation of a particular brain locus. Such an implementation, however, would most likely be highly inflexible in its operation. Such a system would be evidenced by a consistent reference frame for the operation of inhibition. It is much more realistic to view inhibition as a generalized process seen in the operation of almost any brain system, depending on the demands of the task at hand. In a task that requires stimulus identification (Tipper & Driver, 1988; Tipper et al., 1988), response selection depends on semantic information, and inhibition is found to occur within this semantic domain. On the other hand, when a task requires close analysis of perceptual features such as color, inhibition can be seen at this early perceptual stage (DeSchepper, Khurana, O'Connell, & Wilson, 1992). For example, when subjects are required to name the shape of an odd-colored item (e.g., a red object among a background of blue objects), negative priming occurs when the odd-colored item on the subsequent trial takes the color of the background items on the preceding trial (e.g., a blue object among a background of green objects; see Treisman & Sato, 1990). In contrast, the present experiments require spatially directed movements of the hand from a constant start position. In this case, inhibition operates in a spatial domain defined by the relation of the hand position to the target position; that is, it is action centered.

Therefore, the reference frame in which interference is seen and inhibition is directed may depend on the brain system responsible for the task performance. Thus, if a task requires

matching along simple stimulus dimensions such as color, selection may proceed largely within the prestriate cortex, and thus inhibition follows the same retinocentric coordinates of this region (Moran & Desimone, 1985). If the task requires operation of the inferior temporal visual pathway to identify objects, selection (and hence inhibition) will follow the largely object-centered (Hasselmo, Rolls, & Baylis, 1989) or meaning-centered (Baylis, Rolls, & Leonard, 1987) nature of processing on this pathway. The task considered in this study requires the spatial processing performed in the prefrontal and parietal cortices and will consequently show inhibition that follows the predominantly action-centered reference frame of these brain regions. Therefore, selection appears to be highly flexible, being able to access a variety of internal representations (for similar ideas, see Duncan, 1980; Johnston & Heinz, 1978).

The experimental observations reported here have a bearing on our real-world interactions. The next time you are reaching for a glass of beer from a table containing a number of other glasses, consider that the difficulty of that perceptual action task is determined by the relationship between the hand and target-distractor stimuli. If your hand is resting in front of you, then glasses between your hand and your own glass (and if reaching with the right hand, those glasses to the right) cause substantial interference (though we are rarely aware of this), and mechanisms of active inhibition prevent inappropriate action to the irrelevant glasses. This pattern of interference and inhibition is, however, dynamic. If you have just passed, say, a packet of peanuts to a person at the opposite side of the table, and from that location you use the same hand to pick up your glass, then the pattern of interference and inhibition will be quite different. Now glasses at the far side of the table cause the most disruption to your actions and require active inhibition.

References

Bartz, A. E. (1966). Eye and head movements in peripheral vision: Nature of compensatory eye movements. *Science, 152,* 1644.

Baylis, G. C., Rolls, E. T., & Leonard, C. M. (1987). Functional subdivisions of the temporal lobe neocortex. *Journal of Neuroscience, 7,* 330-342.

Biguer, B., Jeannerod, M., & Prablanc, C. (1985). The role of position of gaze in movement accuracy. In M. I. Posner & O. S. M. Marin (Eds.), *Attention and performance XI* (pp. 407-424). Hillsdale, NJ: Erlbaum.

Bootsma, R. J. (1989). Accuracy of perceptual processes subserving different perception-action systems. *Quarterly Journal of Experimental Psychology, 41,* 489-500.

Bridgeman, B., Lewis, S., Heit, G., & Nagle, M. (1979). Relation between cognitive and motor-oriented systems of visual position perception. *Journal of Experimental Psychology: Human Perception and Performance, 5,* 692-700.

Broadbent, D. E. (1958). *Perception and communication.* London: Pergamon Press.

Broadbent, D. E. (1982). Task combination and selective intake of information. *Acta Psychologica, 50,* 253-290.

Cherry, E. C. (1953). Some experiments upon the recognition of speech, with one and with two ears. *Journal of the Acoustical Society of America, 25,* 975-979.

Coles, M. G. H., Gratton, G., Bashore, T. R., Eriksen, C. W., &

Donchin, E. (1985). A psychophysiological investigation of the continuous flow model of human information processing. *Journal of Experimental Psychology: Human Perception and Performance, 11,* 529-553.

DeSchepper, B. G., Khurana, B., O'Connell, K. M., & Wilson, M. (1992). *What is inhibited in negative priming?* Unpublished manuscript.

Downing, C. J., & Pinker, S. (1985). The spatial structure of visual attention. In M. I. Posner & O. S. M. Marin (Eds.), *Attention and performance XI* (pp. 171-187). Hillsdale, NJ: Erlbaum.

Duncan, J. (1980). The locus of interference in the perception of simultaneous stimuli. *Psychological Review, 87,* 272-300.

Eriksen, B. A., & Eriksen, C. W. (1974). Effects of noise letters upon the identification of a target letter in a non-search task. *Perception & Psychophysics, 16,* 143-149.

Eriksen, C. W., Coles, M. G. H., Morris, L. R., & O'Hara, W. P. (1985). An electromyographic examination of response competition. *Bulletin of the Psychonomic Society, 23,* 165-168.

Eriksen, C. W., & Rohrbaugh, J. W. (1970). Some factors determining efficiency of selective attention. *The American Journal of Psychology, 83,* 330-342.

Eriksen, C. W., & St. James, J. D. (1986). Visual attention within and around the field of focal attention: A zoom lens model. *Perception & Psychophysics, 40,* 225-240.

Fisk, J. D., & Goodale, M. A. (1985). The organization of eye and limb movements during unrestricted reaching to targets in contralateral and ipsilateral visual space. *Experimental Brain Research, 60,* 159-178.

Frith, C. D. (1979). Consciousness, information processing and schizophrenia. *British Journal of Psychiatry, 134,* 225-235.

Fuster, J. M. (1980). *The prefrontal cortex.* New York: Raven Press.

Gawryszewski, L. D. G., Riggio, L., Rizzolatti, G., & Umilta, C. (1987). Movements of attention in the three spatial dimensions and the meaning of "neutral" cues. *Neuropsychologia, 25,* 19-29.

Georgopoulos, A. P., Kalaska, J. F., & Massey, J. T. (1981). Spatial trajectories and reaction times of aimed movements: Effects of practice, uncertainty and change in target location. *Journal of Neurophysiology, 46,* 725-743.

Geschwind, N. (1982). Disorders of attention: A frontier in neuropsychology. *Philosophical Transactions of the Royal Society, B298,* 173-185.

Gibson, J. J. (1979). *The ecological approach to visual perception.* Boston: Houghton Mifflin.

Goldberg, M. E., & Segraves, M. A. (1987). Visuospatial and motor attention in the monkey. *Neuropsychologia, 25,* 107-118.

Haber, R. N. (1983). The impending demise of the icon: A critique of the concept of iconic storage in visual information processing. *Behavioral and Brain Sciences, 6,* 1-54.

Hasselmo, M. E., Rolls, E. T., & Baylis, G. C. (1989). The role of expression and identity in the face-selective responses of neurons in the temporal visual cortex of the monkey. *Behavioural Brain Research, 32,* 203-218.

Held, R., & Mikaelian, H. (1964). Motor-sensory feedback versus need in adaptation to rearrangement. *Perceptual and Motor Skills, 18,* 685-688.

Hinton, G. E. (1981). A parallel computation that assigns canonical object-based frames of reference. *Proceedings of the 7th International Joint Conference on Artificial Intelligence.* Vancouver, Canada.

Hinton, G. E., & Parsons, L. M. (1988). Scene-based and viewer-centered representations for comparing shapes. *Cognition, 30,* 1-35.

Hoffman, J. E., & Nelson, B. (1981). Spatial selectivity in visual search. *Perception & Psychophysics, 30,* 283-290.

Humphrey, D. R. (1979). On the cortical control of visually directed

reaching: Contributions by nonprecentral motor areas. In R. E. Talbot & D. R. Humphrey (Eds.), *Posture and movement* (pp. 51–112). New York: Raven Press.

Humphrey, N. K. (1974). Vision in a monkey without striate cortex: A case study. *Perception, 3,* 241–255.

Ingle, D. (1973). Selective choice between double prey objects by frogs. *Brain, Behavior & Evolution, 7,* 127–142.

James, W. (1890). *The principles of psychology.* New York: Henry Holt.

Jeannerod, M. (1986). Mechanisms of visuomotor coordination: A study in normal and brain-damaged subjects. *Neuropsychologia, 24,* 41–78.

Jeannerod, M. (1988). *The neural and behavioral organization of goal-directed movements.* Oxford: Clarendon Press.

Johnston, W. A., & Heinz, S. P. (1978). Flexibility and capacity demands of attention. *Journal of Experimental Psychology: General, 107,* 420–435.

Jones, E. G., & Powell, T. P. S. (1970). An anatomical study of converging sensory pathways within the cerebral cortex of the monkey. *Brain, 93,* 793–820.

LaBerge, D. (1983). Spatial extent of attention to letters and words. *Journal of Experimental Psychology: Human Perception and Performance, 9,* 371–379.

Marr, D. (1982). *Vision.* San Francisco: W. H. Freeman.

Maylor, E. A. (1985). Facilitatory and inhibitory components of orienting in visual space. In M. I. Posner & O. S. M. Marin (Eds.), *Attention and performance XI* (pp. 189–204). Hillsdale, NJ: Erlbaum.

Michaels, C. F. (1989). S-R compatibilities depend on eccentricities of responding hand. *Quarterly Journal of Experimental Psychology, 41,* 263–272.

Miller, J. (1988). A warning about median reaction time. *Journal of Experimental Psychology: Human Perception and Performance, 14,* 539–543.

Moran, J., & Desimone, R. (1985). Selective attention gates visual processing in the extrastriate cortex. *Science, 229,* 782–784.

Neill, S. R., & Cullen, J. M. (1974). Experiments on whether schooling by their prey affects the hunting behavior of celaphod and fish predators. *Journal of Zoology, London, 172,* 549–569.

Norman, D. A. (1981). Categorization of action slips. *Psychological Review, 88,* 1–15.

Posner, M. I., & Cohen, Y. A. (1984). Components of visual orienting. In H. Bouma & D. G. Bouwhuis (Eds.), *Attention and performance X* (pp. 531–554). Hillsdale, NJ: Erlbaum.

Posner, M. I., Nissen, M. J., & Ogden, W. C. (1978). Attended and unattended processing modes: The role of set for spatial location. In H. Pick & E. Saltzman (Eds.), *Modes of perceiving and processing information* (pp. 137–157). Hillsdale, NJ: Erlbaum.

Posner, M. I., & Petersen, S. E. (1990). The attention system of the human brain. *Annual Review of Neuroscience, 13,* 25–42.

Prablanc, C., Echallier, J. F., Komilis, E., & Jeannerod, M. (1979). Optimal response of eye and hand motor systems in pointing at a visual target: I. Spatio-temporal characteristics of eye and hand movements and their relationships when varying the amount of visual information. *Biological Cybernetics, 35,* 113–124.

Rizzolatti, G., Gentilucci, M., & Matelli, M. (1985). Selective spatial attention: One center, one circuit, or many circuits. In M. I. Posner & O. S. M. Marin (Eds.), *Attention and performance XI* (pp. 251–265). Hillsdale, NJ: Erlbaum.

Rizzolatti, G., Riggio, L., Dascola, J., & Umilta, C. (1987). Reorienting attention across the horizontal and vertical meridians: Evidence in favor of a premotor theory of attention. *Neuropsychologia, 25,* 31–40.

Rosenbaum, D. A. (1980). Human movement initiation: Specification of arm, direction and extent. *Journal of Experimental Psychology: General, 109,* 444–474.

Schaffer, W. O., & LaBerge, D. (1979). Automatic semantic processing of unattended words. *Journal of Verbal Learning and Verbal Behavior, 18,* 413–426.

Sparks, D. L. (1988). Neural cartography: Sensory and motor maps in the superior colliculus. *Brain, Behavior & Evolution, 31,* 49–56.

Stravenski, A. A., & Hansen, R. M. (1978). Role of eye position information in visual localization. In J. Senders, D. Fisher, & R. Monty (Eds.), *Eye movement and the higher psychological functions* (pp. 000–000). Hillsdale, NJ: Erlbaum.

Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology, 18,* 643–662.

Tipper, S. P. (1985). The negative priming effect: Inhibitory priming by ignored objects. *Quarterly Journal of Experimental Psychology, 37A,* 571–590.

Tipper, S. P., Brehaut, J. C., & Driver, J. (1990). Selection of moving and static objects for the control of spatially directed action. *Journal of Experimental Psychology: Human Perception and Performance, 16,* 492–504.

Tipper, S. P., & Driver, J. (1988). Negative priming between pictures and words in a selective attention task: Evidence for semantic processing of ignored stimuli. *Memory & Cognition, 16,* 64–70.

Tipper, S. P., MacQueen, G. M., & Brehaut, J. C. (1988). Negative priming between response modalities: Evidence for the central locus of inhibition in selective attention. *Perception & Psychophysics, 43,* 45–52.

Treisman, A. (1988). Features and objects. *Quarterly Journal of Experimental Psychology, 40A,* 201–237.

Treisman, A., & Sato, S. (1990). Conjunction search revisited. *Journal of Experimental Psychology: Human Perception and Performance, 16,* 459–478.

Turvey, M. T., & Carello, C. (1986). The ecological approach to perceiving-acting: A pictorial essay. *Acta Psychologica, 63,* 133–155.

Underwood, G. (1976). Semantic interference from unattended printed words. *British Journal of Psychology, 67,* 327–338.

Verfaellie, M., Bowers, D., & Heilman, K. M. (1988). Attentional factors in the occurrence of stimulus–response compatibility effects. *Neuropsychologia, 26,* 435–444.

von Hofsten, C. (1987). Catching. In H. Heuer & A. F. Sanders (Eds.), *Perspectives on perception and action* (pp. 33–46). Hillsdale, NJ: Erlbaum.

Weiskrantz, K. (1986). *Blindsight: A case study and implications.* Oxford: Clarendon Press.

Wong, E., & Mack, A. (1981). Saccadic programming and perceived location. *Acta Psychologica, 48,* 123–131.